Commercialization Analysis & Roadmap

Title: Catalytic Air Purifiers (CAP) **Date: July 16th, 2012**
IB# 2970
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Technology

Researchers at Lawrence Berkeley National Laboratory (Berkeley Lab) have developed Catalytic Air Purifier (CAP), a system for removing formaldehyde, a known human carcinogen, and other volatile organic compounds (VOCs) from room temperature air in residential, commercial, and industrial buildings at much lower cost than existing technologies. This technology uses catalysts and activated carbon fiber media (ACF) for indoor VOC air cleaning. The catalyst and ACF can be used separately or together. Used together, the first filter removes particles, the catalyst efficiently removes aldehydes (most notably formaldehyde and acetaldehyde, to carbon dioxide and water) and a specific range of VOCs, and the ACF filter adsorbs remaining VOCs and removes ozone (a potent respiratory hazard and pollutant). This Berkeley Lab invention is a 2012 R&D 100 Award Nominee.

Applications

- Active air filtration for residential and commercial buildings and industry
- Passive air filtration (e.g., paint, coatings, wall board)
- Heating, Ventilation, and Air-Conditioning (HVAC) systems

Market

Annual production of formaldehyde in the United States increased from 0.9 million tons in 1960 to 4.5 million tons in 2006. In 2009, 12 companies and their subsidiaries at 39 U.S. manufacturing plants produced formaldehyde[1]. In addition, SRI Consulting forecasts that world consumption will grow at an average annual rate of 4.0% during 2009–2014[2]. Other VOCs also expand the market horizon; for instance, in 2003 global production of acetaldehyde was already 1 million tons[3].

Occupational exposure to formaldehyde can occur in a plethora of industries, including the manufacture of formaldehyde and formaldehyde-based resins, wood composite and furniture production, plastics production, embalming, foundry operations, fiberglass production, construction, agriculture, firefighting, and histology, pathology, and biology laboratories, hair salons and more. In the past, the highest continuous exposure levels were measured during the varnishing of furniture and wooden floors, during the finishing of textiles, in the garment industry, during the treatment of furs, and in certain jobs in manufactured board mills and foundries. Short-term exposure to high levels of formaldehyde has been reported for embalmers, pathologists, and paper workers. Lower levels of exposure have usually been reported for the manufacture of synthetic vitreous fibers, abrasives, and rubber, and in formaldehyde production[4]. VOCs, such as benzene and toluene, are also found in recently renovated and entirely new buildings.

Coinciding with this growth, McIlvaine Company forecasts in their latest Air Filtration and Purification World Markets publication that sales of air filters will increase from $6.6 billion in 2011 to close to $8 billion by 2015[5]. Figure 1 below shows the forecasted steady increase in air filtration sales worldwide. Figure 2 demonstrates that among air filter sales worldwide, commercial and residential sales own the largest segments of the market[5].

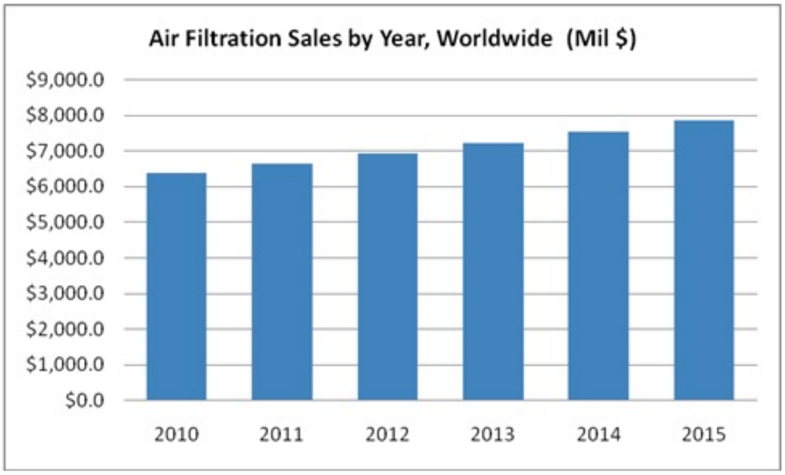
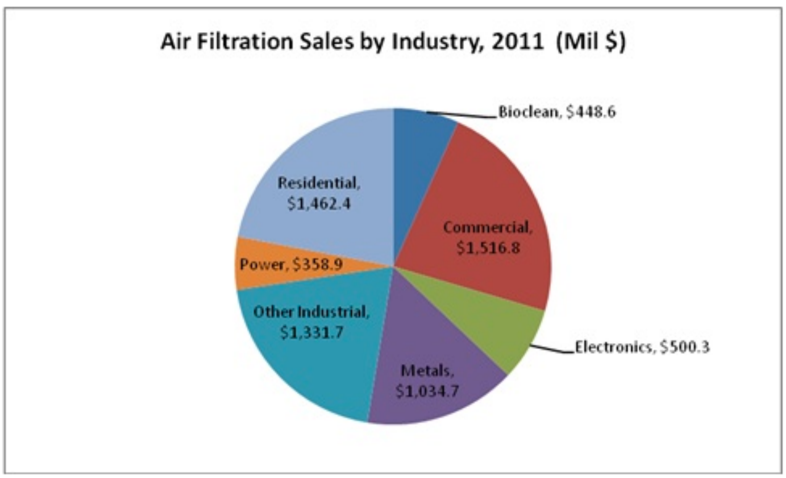


Figure 1- Continuous rise in air filtration sales worldwide from 2011-2015[5]



Air Filtration Sales by Year, Worldwide ($ Million)

Figure 2 – Distribution of air filtration sales worldwide in 2011[5]

Economics

CAP's cost is expected to be approximately $500 per kg of catalyst, or $3 to $5 per m^3/s of airflow for a catalyst-treated filter, when analytical grade reagents are used to synthesize the catalyst. If technical grade reagents are used instead, catalyst cost will be as low as $10 per kg.

Per unit of formaldehyde air cleaning provided, the cost of CAP, when no prefilter is necessary, is less than 8% of the lowest cost competitive technology. In CAP applications with a prefilter, CAP cost less than 40% of the lowest cost competitive technology.

Competitive Landscape

Formaldehyde Removal Media	Granular sodium permanganate on activated alumina	Titanium dioxide catalyst irradiated with UV light	LBNL CAP	LBNL advantage
VOCs other than formaldehyde removed	Hydrogen sulfide, Nitrogen oxide, Nitrogen dioxide, Sulfur dioxide[6]	Broad spectrum, efficiency varies among VOCs	**Acetaldehyde, Acetone, Nonanal, 3-Carene, Limonene, 1 Butanol, Toluene, O-Xylene, Undecane, Benzene[7]**	CAP removes a wide range of VOCs found in indoor air environments.
Products of incomplete decomposition	Probably minimal	Often a problem	**None detected**	No products of incomplete decomposition have been detected with CAP.
Cost of formaldehyde removal media *per kg media*	\$18.7[8]	NA	**Estimated \$540[9]**	Although CAP's cost per kg is higher than others, far less material is required to achieve comparable results.
Mass of media required per gram of formaldehyde removal	25 g[10]	NA	**< 0.04g[11]**	CAP requires the smallest mass of media per gram of formaldehyde removed.
Mass & cost of media per m^3/s *(37 µg/m³ inlet formaldehyde, 65% average efficiency)*	>16.1 kg[12] >\$76	NA	**0.034 kg[13] \$18.6**	CAP has the lowest cost for efficient formaldehyde removal.

	Granular sodium permanganate on activated alumina		Titanium dioxide catalyst irradiated with UV light		LBNL CAP		
Formaldehyde removal system	*Disposable module filled with 15.9 kg of catalyst, plus a separate particle filter*[14]	*Particle filter with 0.37 m² face area and 1.06 kg of catalyst*	Quartz fiber coated with TiO_2 catalyst, UV irradiated[16]	Portable air cleaner[17]	LBNL CAP *catalyst applied to pleated particle filter that replaces filter without catalyst*[18]	LBNL CAP catalyst applied to pleated particle filter, plus a pleated particle prefilter[19]	LBNL CAP Advantage
Incremental Space Required ***(Depth in direction of flow)***	30.5 cm[20]	None (replaces existing particle filters)	100 cm	Unknown	None, replaces existing particle filters	10 cm[21]	CAP requires no extra space or HVAC retrofit to operate.
Incremental airflow resistance ***(with 2.54 m/s face velocity)***	149 Pa[22]	37 Pa[23]	6 Pa	Unknown	~10 Pa[24]	~ 92 Pa[25]	By minimizing airflow resistance, CAP minimized impact on HVAC equipment operating efficiency.
Replacement interval ***(with 37 µg/m³ inlet formaldehyde, 65% average efficiency)***	< 15,600 hours of system operation[26]	< 520 hours of operation[27] < 1,040 hours if inlet conc. is 18.8 µg/m³	Unknown	8,760 hours for lamps, catalyst coated media	2,400 hours of system operation[28]	2,400 hours of system operation[29]	CAP's replacement interval is competitive with most other solutions and coincides with regular HVAC filter replacement intervals.
Incremental energy cost at site ***($0.104 /kWh)***	$215[30]	$54[31]	~$2,000	$2,300	$14[32]	$148[33]	CAP's additional energy costs at the building site are among the lowest.
Total cost for formaldehyde removal system, and energy	> $543[34]	> $2,010 *with 37.5 µg/m3 inlet concentration*[35] > $1,010 *with 18.5 µg/m3 inlet concentration*[35]	~$1,000 for lamps, ~ $2,000 energy, $3,000 total	~$3,700 for filter kits, ~2,300 energy, $6,000 total	$39[36]	$208[37]	The CAP system operates at the lowest overall installed cost.

NOTE:
All systems are assumed to treat 1 m³/s of air continuously for a full year.

Driving Forces and Exposure Guidelines

Studies of workers exposed to high levels of formaldehyde, such as industrial workers and embalmers, found that formaldehyde causes myeloid leukemia, and in rare cases, sinonasal and nasopharyngeal cancer[6]. In addition, VOCs such as benzene, formaldehyde, acetaldehyde, toluene and xylenes are considered high priority pollutants to reduce as a result of their health effects. Figure 1 below shows the rapidly increasing production and consumption of formaldehyde in China, as well as comparison of global output[6].

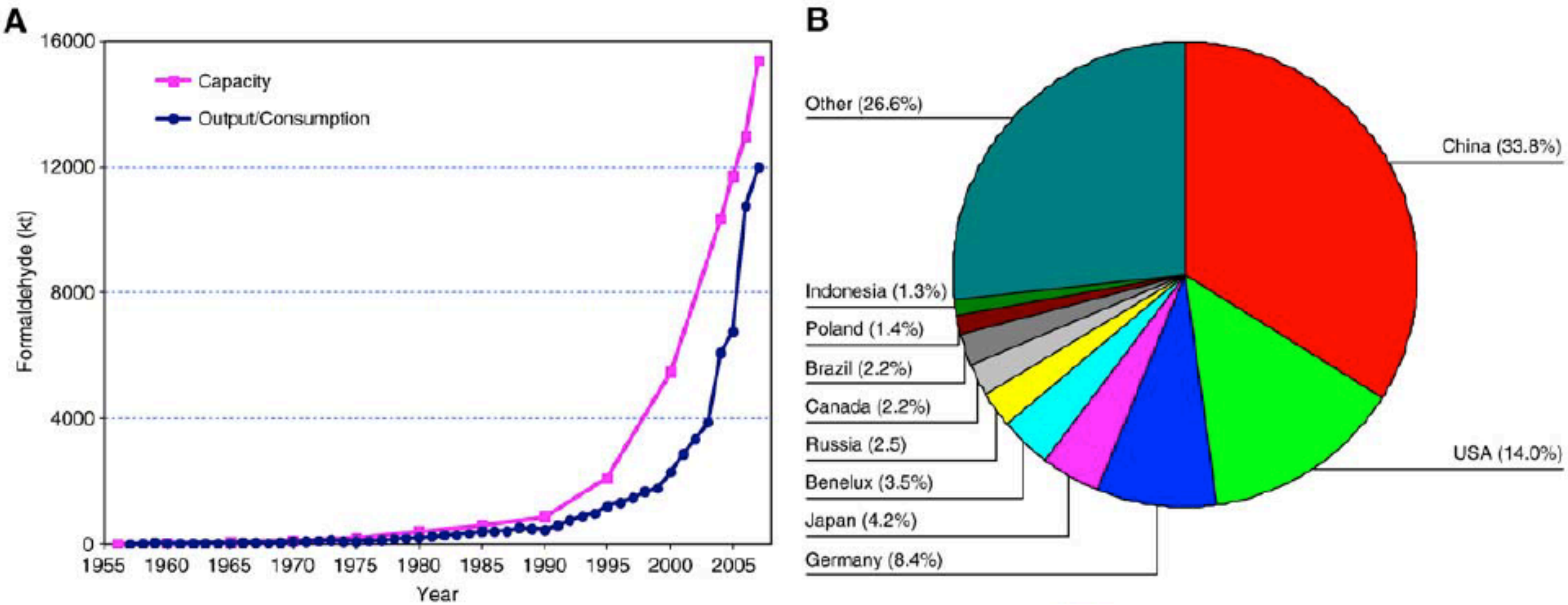


Figure 3 - A) Levels of formaldehyde production capacity, output and consumption in China from 1956-2007; In 2007, the production capacity was 15,393 kt, while output and consumption were 12,000 kt and 11,990 kt respectively. B) Countries contributing to formaldehyde output worldwide. The total global output for formaldehyde was 31,940 kt in 2006[6].

The World Health Organization (WHO) has developed a guideline for formaldehyde in non-occupational settings at 100 ppb (0.123 mg/m3) for 30 minutes, and the National Institute of Occupational Health (NIOSH) standard is 16 ppb (time weighted average). The reference exposure level set by the California EPA is much lower— 7 ppb (.009 mg/m3) for both 8-hour and chronic exposure periods. Many commercial and residential buildings have formaldehyde concentrations of 10 to 20 ppb, exceeding the guidelines set by the California Environmental Protection Agency and NIOSH. Nonetheless, these are merely guidelines, and strict regulation of formaldehyde exposure is yet to be instilled. Despite being a carcinogen, until clear mandates are put in place, the lack of enforced regulation is a potential barrier to widespread adoption.

Pros and Cons

Pros

- Lowest cost of use.
- CAP removes a broader range of harmful VOCs than the lowest cost competitive technology.
- Completely decomposes formaldehyde into nonharmful carbon dioxide and water.
- Less costly than chemisorbents.
- Long term efficiency; CAP initially removes 80% of formaldehyde and continues to remove 50% after 2,400 hours of continuous operation in a building.
- More convenient to handle and replace (applied to air filters) than activated carbon, which impedes airflow, requires higher fan power, and doesn't remove formaldehyde.
- Ease of retrofit. No hardware changes are required.
- Reduces energy use / cost of running ventilation systems in buildings to remove VOCs.

Cons

- Building owners may not be motivated to take on any additional cost to remove formaldehyde if predicted levels fall below OSHA requirements.
- Passive air filtration applications (e.g. paints and coatings) have not shown any increase in efficiencies to date, and further experimentation and testing is required to prove feasibility

Intellectual Property

A patent application has been filed and is pending.

Readiness

CAP uses new, nanostructured manganese oxide catalysts produced in powder form and applied directly to particle filters. Therefore, the technology can be implemented without redesigning or reconfiguring existing building HVAC systems by simply replacing worn particle filters with HVAC-compatible new ones that contain CAP.

HVAC manufacturing steps are discussed in detail here: http://www.madehow.com/Volume-7/Air-Purifier.html#b

Licensing Strategy

Widespread adoption of this technology can foster high societal returns, and as such, targeting several non-exclusive licenses or an exclusive license to a company that would manufacture and sell to multiple air filtration companies are two plausible licensing strategies. Appendix A shows a list of the key and niche players in air filters and filtration equipment worldwide market[39]

Licensing should be targeted to air filter companies that supply their products and services to wood and furniture manufacturers, textile/garment companies, board mill manufacturers and foundries as well as companies that have a focus on energy efficient air filter systems.

Next Steps

The next steps involve synthesizing larger sample batches and researching technical grade catalysts as opposed to analytical grade catalyst.

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Appendix A (Green suggests companies whose business is strongly aligned to the UCAP technology.)

Table 1 - List of the main air filter manufacturers

COMPANY	NOTES	Website
3M Company (USA)	Commercial HVAC (Filtrete™)	http://bit.ly/KKznuE http://bit.ly/LEqO0R (Filtrete)
Aerospace America Inc. (USA)	Standard air filtration	http://bit.ly/MlZyn0
Air Filter Service Company (USA)	Standard HVACs, Camsorb™ commercial filters	http://bit.ly/LJ7l2p
Air Filtration Systems LLC (USA)	Industrial Apps, Wood particulate collectors, fume/vapor removals, Cost of Heating Loss Due to Ventilation	http://bit.ly/LJ7l2p
Airtech Japan Ltd. (Japan)	Airborne Molecular Contamination (AMC). Boron and Phosphorus, Alkaline gasses NH3 and NH2, Acidic gasses, Organic Matter, Silicones, and Plasticizers. Activated Carbon Fiber Filter, Cation and Anion filters	http://bit.ly/KBF6l8
American Air Filter (AAF) Int'l (USA)	Manufacturing facilities installations	http://bit.ly/MyQ34r
Bruce Air Filter Company (USA)	Large retail store chains, office building and government facilities	http://bit.ly/MHQXwS
Camfil Farr (USA)	Energy savings (low energy air filters), industrial dust and fume collectors for workplace	http://bit.ly/KQ4Yex
Champion Laboratories, Inc. (USA)	Heavy liquid filter focus, Air filters predominantly for automotive engines	http://bit.ly/KX75sd
Clarcor, Inc. (USA)	Air filters, antimicrobial filters, dust collection systems, electrostatic air filtration, carbon filters, paint overspray filters, HEPA filters, air pollution control systems. Apps include commercial & industrial buildings, factories & plants	http://bit.ly/KxSwP2
Purolator Products Air Filtration (USA)	Subsidiary of Clarcor; PURO® gas phase filters/specialty products for commercial and industrial buildings	http://bit.ly/KX8LSE
Cummins, Inc. (USA)	Fuel and engine systems	http://bit.ly/r7nssU
Cummins Filtration (USA)	See above	http://bit.ly/r7nssU
Donaldson Co., Inc. (USA)	Chemicals and plastics, woodworking, metalworking and many more. Highly	http://bit.ly/MyWjZP

Dust Free Inc. (USA)	Residential products	http://bit.ly/a5vFqF
Fiberweb Filtration (UK)	Industrial Heating Ventilation Air Conditioning (HVAC), own melt-blown technology	http://bit.ly/KDU3P5
Filtration Group Inc. (USA)	Industrial HVACs, heavy liquid filtration focus; Makes fiber for filters. Highly customized products	http://bit.ly/MDQnN0
Filtration Systems Products Inc. (USA)	Industrial applications. Custom manufacturing capabilities for specialized systems	http://bit.ly/MaKSIT
Filtrauto S.A. (France)	Vehicle applications	http://bit.ly/MNQ56z
Flanders Corp. (USA)	Wide product range, largest US manufacturer of air filters, many industries including material processing	http://bit.ly/NfJEh2
Precisionaire Inc. (USA)	Subsidiary of Flanders Corp. (see above)	http://bit.ly/NfJEh2
Freudenberg Group (Germany)	Vehicle applications	http://bit.ly/PDaOOn
Freudenberg Nonwovens L.P. (Germany)	Subsidiary of Freudenberg Group. (see above)	http://bit.ly/PDaOOn
Lydall Inc. (USA)	Wide product range, large US manufacturer for many industries including chemical processing	http://bit.ly/Mz3IbE
Mann Hummel (Germany)	Air filters for industrial manufacturing sectors.	http://bit.ly/KXhbcD
Nordic Air Filtration (Denmark)	Custom air filter media; many industrial types including wood processing, and chemical plants	http://bit.ly/Lk3OrJ
Pall Corporation (USA)	Primarily liquid filtration applications	http://bit.ly/qLkYli
Purafil Inc. (USA)	Custom air filter systems according to the types and levels of gases present (wide range of products and targeted industries)	http://bit.ly/MDSe8j
SPX Corporation (USA)	Hankison brand, energy saving focus, multi-industry manufacturing, Fortune 500	http://bit.ly/NiHYzR
Trion Inc. (USA)	Metals, plastics, woods, grains and food, pharmaceuticals, minerals, or textiles	http://bit.ly/LmJrdv
Waltz-Holst Blow Pipe Co. (USA)	Furniture manufacturing, molding and trim production, cabinet making, sawmills, particle board manufacturing, metal smelting, foundries, metal extrusion, chemical manufacturing, paper manufacturing	http://bit.ly/L0TnVm

References

[1] http://ntp.niehs.nih.gov/ntp/roc/twelfth/profiles/Formaldehyde.pdf

[2] http://www.icis.com/v2/chemicals/9076013/formaldehyde/uses.html

[3] http://en.wikipedia.org/wiki/Acetaldehyde#Production

[4] http://ntp.niehs.nih.gov/ntp/roc/twelfth/profiles/Formaldehyde.pdf

[5]http://home.mcilvainecompany.com/index.php?option=com_content&view=article&id=192

[6] http://www.purafil.com/products/media/sp_media.aspx

[7] Based on test results in Sidheswaran et al (2100a, 2011b).

[8] Based on quote from vendor (Air Filter Control Corp, San Jose, CA)

[9] Estimated by an experienced chemical engineer accounting for cost of analytical grade reagents (dominant cost), equipment required, operation and maintenance, marketing, and management. If technical grade reagents can be used, which has not been proven, the catalyst cost would be diminished by approximately a factor of 50.

[10] Based on product literature (http://www.purafil.com/products/media/sp_media.aspx), the granular sodium permanganate on activated alumina ($NaMnO_4$- Al_2O_3 catalyst) removes 4% of its weight of formaldehyde. In practice, with other organic compounds in the air consuming $NaMnO_4$-Al_2O_3 catalyst, the removal capacity for formaldehyde may be lessened; however, we assumed 4% by weight.

[11] Based on formaldehyde removal over time as reported in Sidheswaran et al (2011b) With 4.34 g catalyst per m2 filter and 0.5 m/s velocity, average inlet formaldehyde = 37 µg/m3, average removal efficiency was 65% over 100 days. Catalyst continued to be effective so actual number is less than 0.04 g catalyst per 1g of formaldehyde removed

[12] Calculated based on the mass of the $NaMnO_4$- Al_2O_3 catalyst in the module, the air flow rate (0.472 m3/3), the assumption that the $NaMnO_4$- Al_2O_3 catalyst removes 4% of its weight of formaldehyde, and quoted price of $18.70 per kg.

[13] Based on test results in Sidheswaran et al (2011b) demonstrating 65% average formaldehyde removal efficiency over 2400 h with 4.34g of catalyst per square meter of filter media and 0.5 m/s air speed through media.

[14] This system contains trays of the $NaMnO_4$- Al_2O_3 catalyst configured in a manner to provide adequate mass transfer for formaldehyde removal and reasonable pressure drop.

[15] The Purafilter is a MERV 8 particle filter containing the $NaMnO_4$- Al_2O_3 catalyst. It can be used in place of existing filters.

[16] In our tests of a prototype with 0.1 m3/s airflow and 72 W of lamp power, formaldehyde removal efficiency was 13% and pressure drop was 3 Pa. The prototype had photocatalytic media

only downstream of the lamps, wasting half of lamp power. By placing photocatalytic media upstream and downstream of the lamps, we project a 24% formaldehyde removal efficiency and a 6 Pa pressure drop. To scale up to a 1 m3/s unit we multiply fan and lamp power by 10. To scale up to 65% formaldehyde removal efficiency, we scale up by 65%/24% = 2.7. Thus total lamp power to provide formaldehyde removal equivalent to 65% in 1 m3/s airflow is 0.072 kW x 10 x 2.7 = 1.94 kW. Annual lamp energy cost = 8760 h x 1.94 kWh x $0.104/kWh = $1767. Fan energy cost, calculated as indicated in note 13 is $232. Total energy cost = $2000. We used the $19 cost for 30W germicidal lamps from asltg.com, although lamps were 36 W.

[17] Based on product literature for Innovative Labs Sonomo Breeze SB200 air cleaner with 0.094 m3/s air flow, 240 W power, reported 90% formaldehyde removal efficiency, $350 price for filter kit replaced annually, scaled up to 1 m3/s and adjusted for 90% efficiency relative to 65% reference case efficiency. Initial cost of unit and cost of lamps not included in estimates.

[18] We assumed 4.34 g catalyst per m2 of filter media is applied to a MERV 8 particle filter (American Air Filter Perfect Pleat SC M8) which has 0.37 m2 nominal face area, 2.04 m2 of filter media, 0.94 m3/s airflow, a pressure drop of 80 Pa when new and 249 Pa when replaced. Price is $9.83 per filter (http://www.thefilterstore.com).

[19] For this method of using the catalyst, we assume that the catalyst treated filter is a supplemental filter located downstream of the existing MERV 8 particle filter. In this case, the system imposes a larger incremental airflow resistance, and calculations must account for the cost of incremental filter media.

[20] Depth of the Purafil CK-12/24 Mediapak disposable plastic module in direction of airflow

[21] Depth of filter to which catalyst is applied

[22] From manufacturer's product literature (http://www.purafil.com)

[23] Estimated from initial resistance of Purafilter (107 Pa per product literature) minus the initial airflow resistance of the particle filter replaced (see note 5)

[24] The increase in pressure drop increases approximately linearly with particle loading on the filter (Hinds and Kadrichi 1997). The medium efficiency filters to which the catalyst is applied is designed to hold at least 80 g of collected particles per square meter of filter media and have an increase in airflow resistance of 179 Pa. Thus, the estimated increase in pressure drop from application of the catalyst is 5.4% of 179 Pa or 10 Pa.

[25] Because catalyst treated filter is proceeded by a particle filter, particle deposition on the catalyst treated filter is reduced by ~ 75% and the pressure drop of the catalyst treated filter is projected to increase by only 45 Pa over the 2400 h deployment. Thus, the average airflow resistance is estimated to be 102 Pa (initial 80 Pa, final 125 Pa, average 102 Pa).

[26] Based on airflow through module of 0.472 m3/s and assumption that the $NaMnO_4$- Al_2O_3 catalyst can remove 4% by weight of formaldehyde (note 16). In practice life will be smaller because other VOCs consume the $NaMnO_4$- Al_2O_3 catalyst and because removal efficiency will fall below 65% well before all media is consumed by chemical reaction.

[27] Based on air flow rate, inlet formaldehyde concentration and formaldehyde removal efficiency given in prior notes and, the assumption that the$NaMnO_4$- Al_2O_3 catalyst removes 4% of its weight of formaldehyde

[28] Per Sidheswaran et al (2011b), 65% average efficiency maintained over 2400 h with average inlet formaldehyde of 37 µg/m3 and velocity of 0.5 m/s when inlet air was unfiltered indoor air.

[29] See note 28

[30] Calculated as indicated in note 33, but with airflow resistance of 149 Pa (see note 22).

[31] Calculated as indicated in note 33, but with incremental airflow resistance of 37 Pa (note 10).

[32] Per Sidheswaran et al (2011b), 65% average efficiency maintained over 2400 h with average inlet formaldehyde of 37 µg/m3 and velocity of 0.5 m/s when inlet air was unfiltered indoor air.

[33] Fan motor power = [Flow Rate (1 m3/s) x Pressure Drop (102 Pa)]/[fan efficiency (0.7) x motor efficiency (0.9)] = 162 W. Energy cost = fan power x 8760 h x $0.104/kWh

[34] Sum of energy cost (note 30), price of modules ($275 quote from Air Filter Control Corporation, San Jose, CA), airflow per module of 0.473 m3/s, and module life (note 26)

[35] Sum of energy cost and product cost ($112 for 24 x 24 x 4 Purafilter based on quote by Air Filter Control Corporation, San Jose, CA), minus the cost of reference particle filter without sodium permanganate ($10 for 24 x 24 x 4), accounting for flow rate for filter (0.94 m3/s) and replacement interval

[36] Based on replacement interval, cost of catalyst, assuming the cost of applying the catalyst to the filter (a spray application) is $1 per square meter of filter media

[37] Includes costs detailed in note 18, energy cost (note 4), and cost of filters (see note 18)

[38] http://superfund.berkeley.edu/pdf/117.pdf

[39] http://www.businesswire.com/news/home/20110615005793/en/Research-Markets-Air-Filters-Filtration-Equipment--